

Switching-regulator design lowers noise to 100 μV

JIM WILLIAMS, LINEAR TECHNOLOGY CORP

Size, output-flexibility, and efficiency advantages have made switching regulators common in electronic apparatus. The emphasis on these attributes has resulted in circuitry requiring minimal board area and with 95% efficiency. Although these advantages are welcome, they necessitate compromising other parameters.

The switched-mode power delivery that permits high-efficiency conversion also creates wideband harmonic energy. This undesirable energy appears as radiated and conducted components, or "noise." Switching-regulator output noise is actually coherent, high-frequency residue that directly relates to the regulator's

Expending unconscionable amounts of bypass capacitors, ferrite beads, shields, Mumetal, and aspirin to ameliorate noise-induced effects is no longer the only way to tackle switching-regulator noise. Using a low-noise IC, you can now design switching converters with only 100 μV of noise.

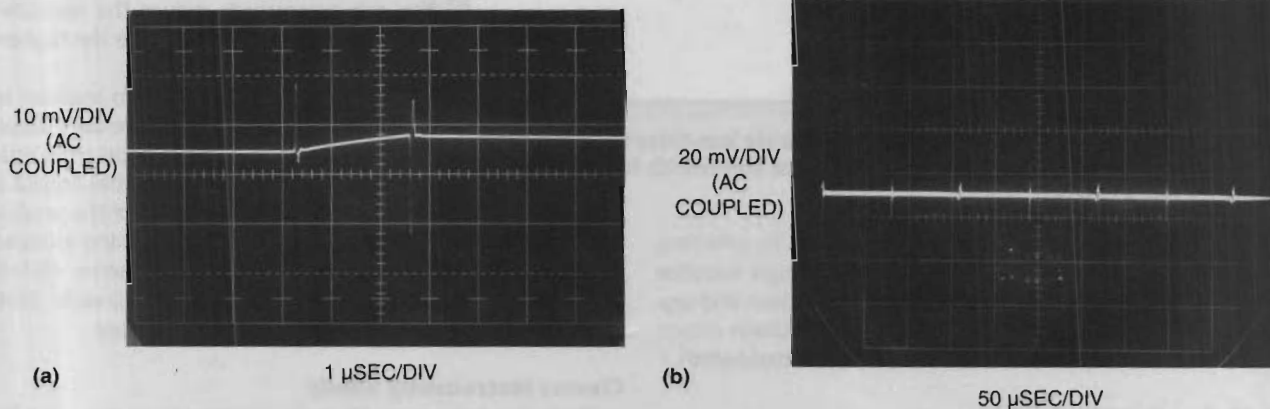
switching. Unfortunately, it is almost universal practice to refer to these parasitics as "noise."

The finite-storage capacity of a switching regulator's output filter components causes a slow, ramping output ripple, and the switching transitions cause quickly rising spikes (Figure 1a). Adequate filtering and linear

postregulation can eliminate the ripple, but the wideband spikes remain (Figure 1b). These fast spikes' high-frequency content often corrupts associated circuitry, degrading performance or even disabling operation.

Noise gets into adjacent circuitry via conduction from the

FIGURE 1



The typical switching regulator's output (a) has wideband spikes that are difficult to suppress. Adding a linear regulator can eliminate ripple, but the wideband spikes remain (b).

LOW-NOISE SWITCHING REGULATORS

regulator-output lead, conduction back to the driving source ("reflected" noise), and radiation. These multiple transmission paths combine with the high-frequency content, making it difficult to suppress noise. One approach to ameliorate noise-induced effects is to use several bypass capacitors, ferrite beads, and shields and to use Mumetal. Alternative approaches involve synchronizing switching-regulator operation to the host system or implementing an "interrupt-dri-

ven" power supply by turning off switching during critical system operation. Another approach places critical system operations between switch cycles—running between electronic raindrops.

Minimize harmonics, noise

The most attractive design alternative to lowering switching noise is to use an inherently low-noise switching regula-

SPECIFYING AND MEASURING LOW-OUTPUT NOISE

Many ways exist to specify noise in a switching regulator's output. Common industrial practice specifies peak-to-peak noise in a 20-MHz bandpass. Realistically, spectral energy beyond 20 MHz readily upsets electronic systems, and this 20-MHz specification restriction benefits no one.

Measurements of a commercially available regulator confirm this point. Noise measurements in a 1-MHz bandpass indicate that the device meets its claimed 5-mV p-p noise specification. Increasing the bandwidth to 10 MHz shows larger amplitudes of 6 mV p-p. A 50-MHz bandwidth unveils spikes measuring 30 mV p-p, or six times the specified limit.

Thus, 100 MHz is a more appropriate bandwidth over which to specify peak-to-peak noise. Reliable low-level measurements in this bandpass require carefully choosing instru-

which produces a less than 1-mV version of the step. The amplifier provides 40 dB of gain ($A=100$), and the oscilloscope displays the result. The front-to-back cascaded bandwidth of this system should be about 100 MHz, or a rise time of 3.5 nsec. **Figure B** confirms the test setup's 3.5-nsec rise time and displays about 100 μ V of noise.

Measure noise floor

To test for noise of the test setup alone, remove the input and turn off the switching regulator to verify a 100- μ V noise floor (**Figure C**). This amount of noise corresponds to the noise of a 50 Ω resistor in a 100-MHz bandwidth.

Then, measuring the noise that the text's **Figure 2a** produces involves ac coupling the circuit's output into the test setup's input. Maintaining coaxial connections is important to preserve measurement integrity. The output noise in **Figure D** shows barely visible switching artifacts at the fourth, sixth, and eighth vertical lines in a 100-MHz bandpass. You can more clearly see the fundamental 40-kHz ripple, although the noise floor similarly dominates this ripple.

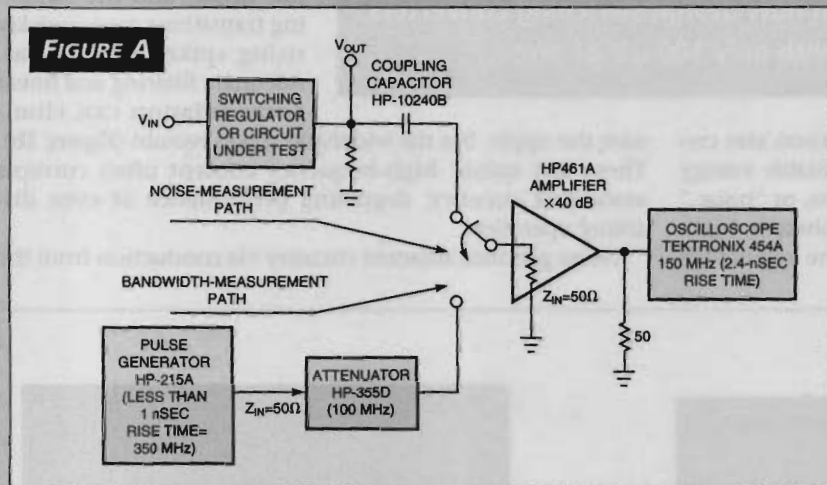
Restricting the measurement bandwidth to 10 MHz reduces noise-floor amplitude, but switching noise and ripple amplitudes remain the same. This result indicates that no signal power occurs beyond 10 MHz. You can successively reduce the measurement bandwidth to determine the highest frequency content.

You can also use a spectrum analyzer to study noise levels. With **Figure 2a's** circuit ac coupled into an HP4195A spectrum analyzer with a 500-MHz sweep, the output is essentially identical to a plot of the analyz-

er's noise floor. The analyzer cannot detect switching-induced noise in a 500-MHz bandpass. You can detect some 40-kHz fundamental-related components in a 1-MHz-wide plot, although analyzer noise limits the rest of the sweep.

Choose instruments wisely

These low-level measurements require preamplification for the oscilloscope. The current generation of oscilloscopes rarely has sensitivities greater than 2 mV/div, although older instru-



The proper test setup is critical to making accurate low-noise measurements. The instruments you choose must have sufficient bandwidth to capture high-frequency noise spikes.

mentation and connections. You need to begin by selecting test instrumentation and verifying the test setup's baseline noise and bandwidth (**Figure A**). Good connection and signal-handling technique and judicious instrumentation choice should yield a 100- μ V noise floor in a 100-MHz bandwidth.

Verify bandwidth

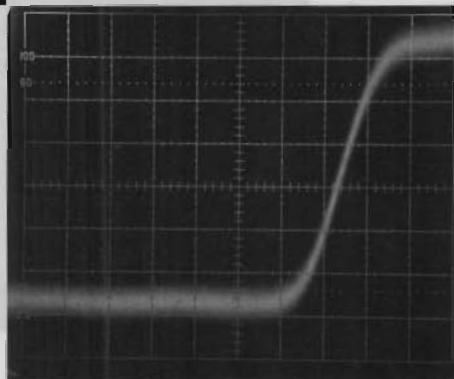
To test the system's bandwidth, use a pulse generator to supply a subnanosecond rise-time step to the attenuator,

tor because it eliminates noise concerns and maintains system flexibility. Such a regulator also doesn't force you to make the compromises of synchronized approaches.

The key to designing an inherently low-noise regulator is to minimize harmonic content in the switching transitions. Slowing the switching interval minimizes harmonics, although power dissipated during the transition causes some efficiency loss. Reducing switch-repetition rate can

largely offset the losses, resulting in a reasonably efficient design with small magnetics and the desired low noise. Noise reduction by restricting harmonic generation is not new, but previous implementations were complex and narrowly applicable. You can use a monolithic approach, the Linear Technology LT1533, over a range of magnetics and applications (see box "A practical, low-noise monolithic regulator," pg 160).

FIGURE B

100 μ V/DIV

2 nSEC/DIV

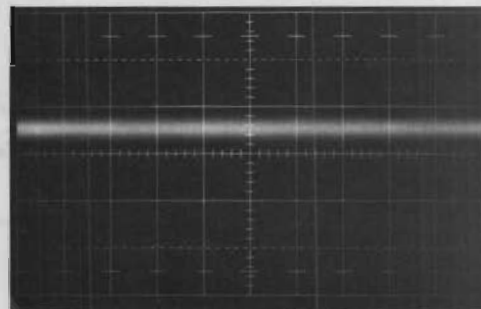
Applying a subnanosecond rise-time step to the test setup confirms a rise time of 3.5 nsec, or bandwidth of 100 MHz.

ments offer more capability. In keeping with instrumentation trends, which emphasize digital-signal acquisition rather than analog-measurement capability, many manufacturers no longer produce the wideband, low-noise preamplifiers and oscilloscope plug-ins for these noise measurements, such as the HP461A preamp and the Tektronix (Beaverton, OR) 7A13 plug-in. However, you can often obtain these units from secondary suppliers. Also, vendors such as Stanford Research Systems (Sunnyvale, CA) and Preamble (Beaverton, OR) are beginning to produce preamplifiers for these types of measurements.

The monitoring oscilloscope should have adequate bandwidth and exceptional trace clarity; analog oscilloscopes are unmatched in trace clarity. The exceptionally small spot of these instruments is well-suited to low-level noise measurement. The digitizing uncertainties and raster-scan limitations of digital sampling oscilloscopes impose display-resolution penalties. Many of these scopes' displays do not even register the small levels of switching-based noise.

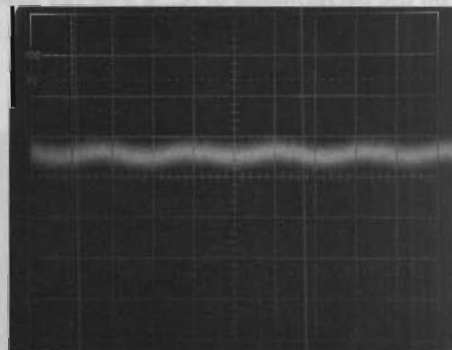
The preamplified oscilloscope is also a more sensitive tool for these measurements because its triggered operation has the advantage of synchronous detection. You can demonstrate this feature by free-running the preamplified oscillo-

FIGURE C

100 μ V/DIV20 μ SEC/DIV

With no input and the regulator off, the noise floor of the test setup is less than 100 μ V.

FIGURE D

100 μ V/DIV10 μ SEC/DIV

With confidence in the test setup, you can measure the output noise of the circuit as approximately 100 μ V.

scope sweep; the switching-related components are indistinguishable in the noise background.

LOW-NOISE SWITCHING REGULATORS

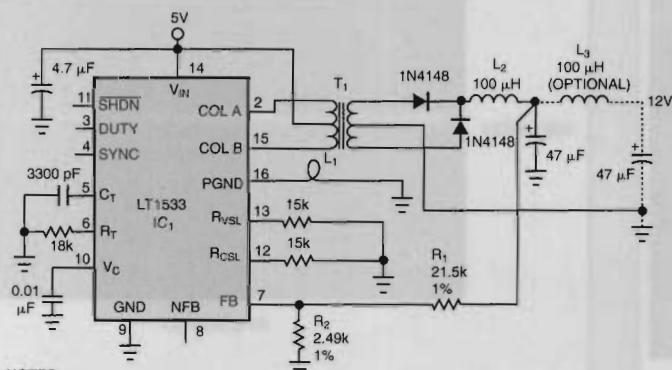
The 40-kHz, 5-to-12V converter in **Figure 2a** uses the low-noise LT1533 in a push-pull, "forward" configuration. The ratio of feedback resistors R_1 and R_2 produces a 12V output. A two-section LC filter provides high-ripple attenuation, although a one-section LC would also perform well. A noteworthy characteristic of this circuit is that the output filter—which filters the 40-kHz fundamental-related ripple—does not affect the high-frequency noise content, because the circuit itself develops little high-frequency energy.

The magnetics considerations for this circuit are simple.

The regulator's symmetrical push-pull drive makes transformer behavior quite predictable. Thus, you can usually specify the transformer you need by indicating the operating frequency, power, and desired input/output voltages. The circuit in **Figure 2a** and related circuits can use a number of transformers with nominal input voltages of 5V and output powers of 1.5 to 10W.

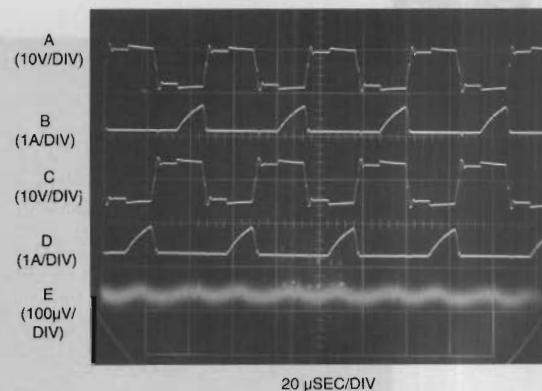
Also, the inductors in **Figure 2a** and related circuits that follow have no special characteristics. This forward converter requires an inductor ahead of its filter capacitor, although

FIGURE 2



NOTES:

T₁: CTX02-13665-X1 (COILTRONICS INC, BOCA RATON, FL).
 L₁: B-07T (COILCRAFT INC, CARY, IL), 22-nH TRACE INDUCTANCE.
 FERRITE BEAD (FERRONICS INC, FAIRPORT, NY) WITH ONE OR TWO TURNS OF WIRE, OR FIVE TURNS OF #28 WIRE.
 L₂, L₃: CTX100-3 (COILTRONICS).



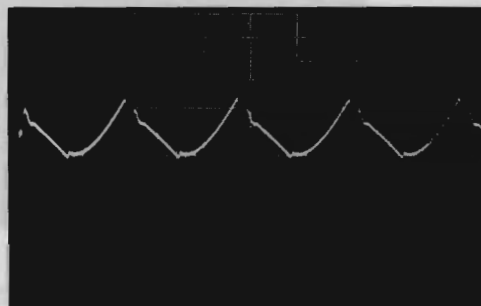
TRACE DESCRIPTION

TRACE	DESCRIPTION
A	SWITCHING-TRANSISTOR COLLECTOR VOLTAGE
B	SWITCHING-TRANSISTOR CURRENT
C	SWITCHING-TRANSISTOR COLLECTOR VOLTAGE
D	SWITCHING-TRANSISTOR CURRENT
E	CIRCUIT OUTPUT NOISE

Based on the performance of IC₁, a 5-to-12V converter (a) has only 100 μV of output noise (b, Trace E).

FIGURE 3

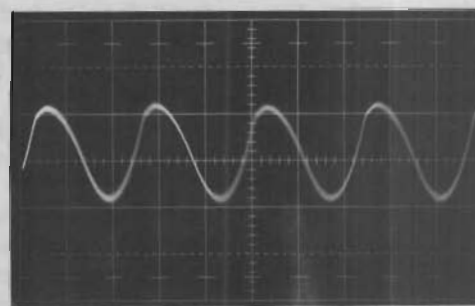
5 mV/DIV



(a)

10 μSEC/DIV

10 mA/DIV
(AC COUPLED
ON 200-mA
DC LEVEL)



(b)

10 μSEC/DIV

Ripple at the first LC output has no wideband spikes (a). The input current (b) contains small sinusoidal variations, which the input supply can easily absorb.

LOW-NOISE SWITCHING REGULATORS

additional LC filtering is optional. Other application circuits, such as a bipolar floating-output converter, need no output inductor unless heavily loaded, although you may still want to use LC sections for best possible ripple attenuation. In any case, inductor characteristics are unimportant. All of the low-noise circuits use Octa-Pak type toroidal core-based inductors (Coiltronics Inc, Boca Raton, FL.)

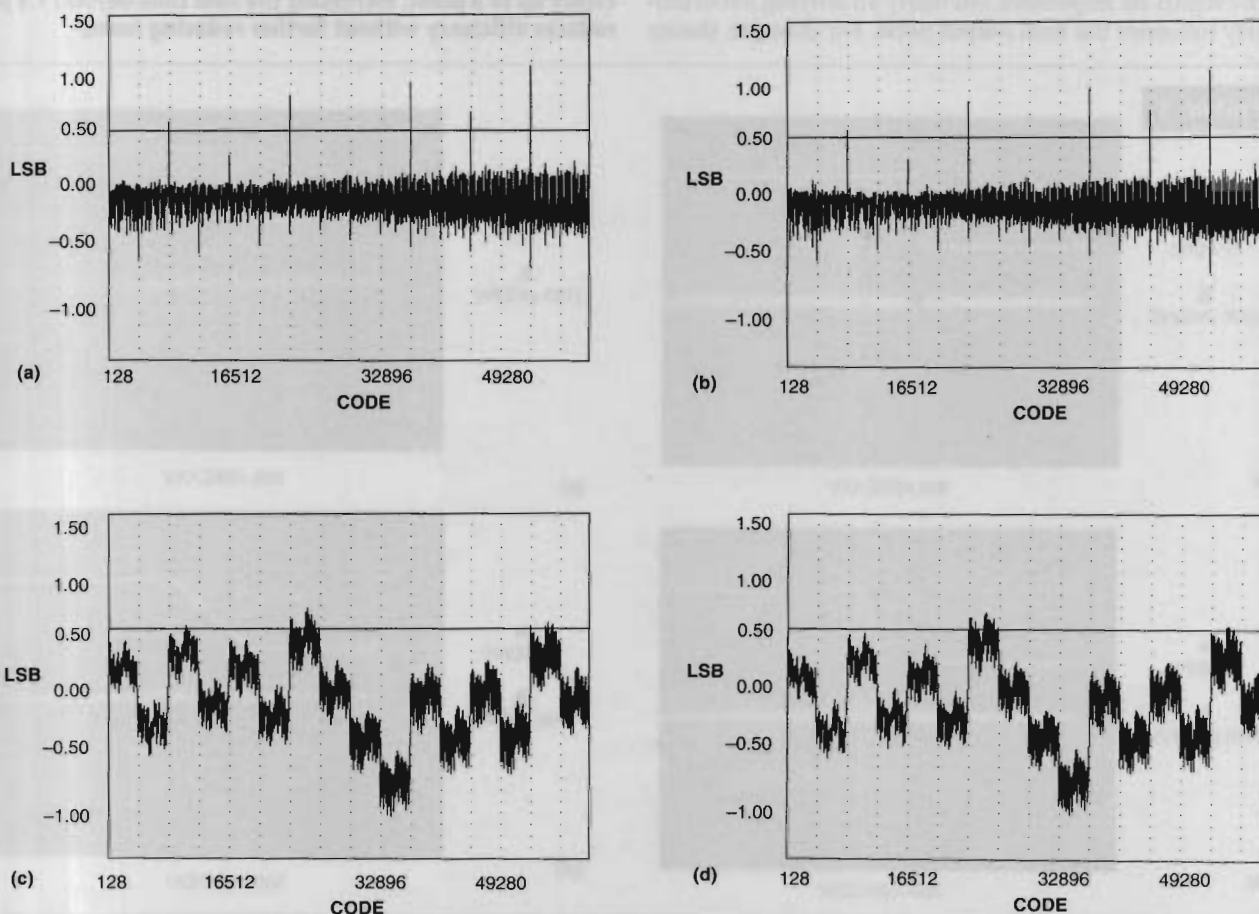
One inductor, L_1 , used in the power-ground return (Pin 16) of the IC, compensates for the output-current control loop. In practice, L_1 can take several forms, including a length of pc-board trace; a small coil of wire; a ferrite bead; or a packaged, 22-nH inductor.

Figure 2b details circuit operation. Traces A and C are switching-transistor collector voltages; B and D are the respective transistor currents. Trace E is the test setup's output, representing circuit-output noise. Wideband spiking and ripple, just visible in the noise floor, are within 100 μ V,

even in a 100-MHz bandpass. This performance is even better than the photo shows. Removing all probes from the breadboard leaves only Trace E's coaxial connection and eliminates any possible ground-loop-induced error. The resultant trace shows 40-kHz ripple with about the same amplitude as in Figure 2b. Switching-related spikes, just faint outlines in the noise, decrease. Low-frequency noise is rarely a concern, although it is also well below 100 μ V.

Other noteworthy signals in the circuit are the output of the first LC-filter section and the input current. At the first LC-filter section's output, you can clearly see the ripple's 40-kHz fundamental, but no wideband spikes are visible (Figure 3a). Expanding the time scale shows no observable high-frequency harmonics or spikes. The input current has a 40-kHz fundamental-related sinusoidal component (Figure 3b), and the driving source can easily handle these variations. Otherwise, this signal contains no high-frequency content.

FIGURE 4



Crossplots of a 16-bit A/D converter's differential (a, b) and integral (c, d) linearity show virtually imperceptible differences between performance with a bench supply (a, c) and the LT1533-based supply circuit (b, d), respectively.

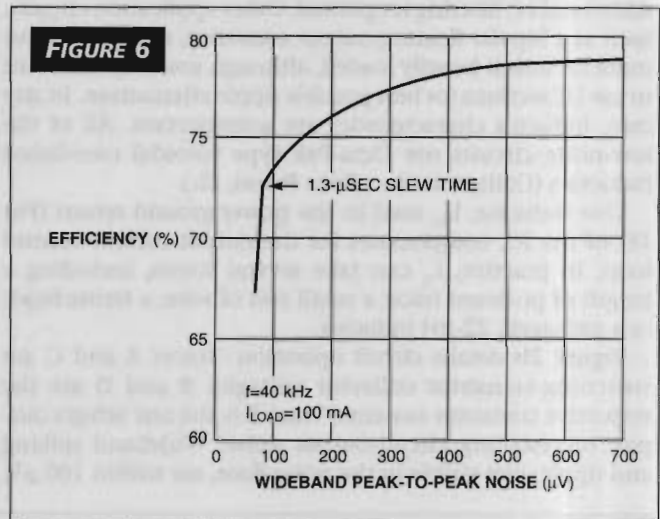
LOW-NOISE SWITCHING REGULATORS

Making these low-noise measurements requires specialized techniques with a precise test setup (see box "Specifying and measuring low-output noise"). Measurement technique, although not a way to obtain the lowest noise performance, must be trustworthy. You can lose hours chasing "circuit problems" that are manifestations of poor measurement techniques. Following the proper techniques prevents you from pursuing solutions to circuit noise that isn't really there.

System measurements are the real test

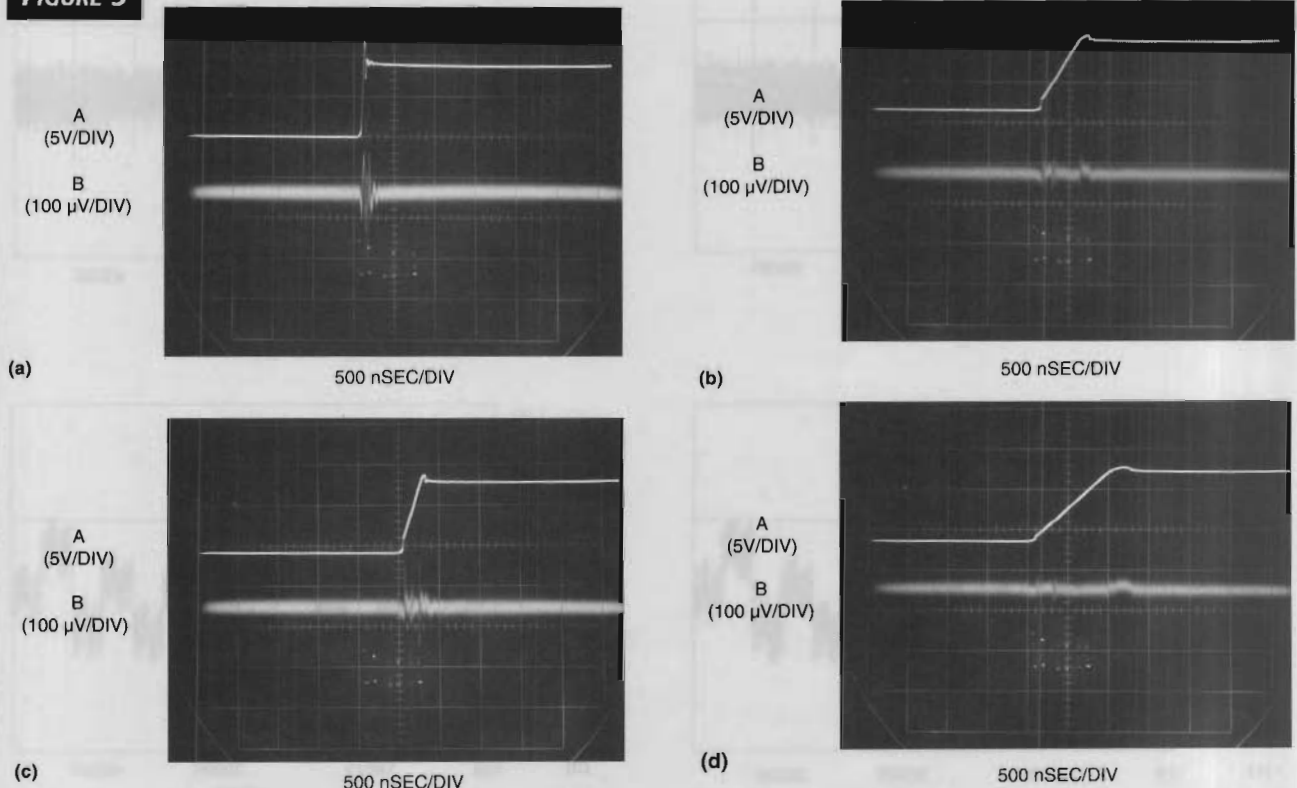
In the final analysis, the effect of switching-regulator output noise on the system is the ultimate test, and measuring the noise coupled into a 16-bit converter is a particularly stringent test. Crossplots of integral and differential nonlinearity (Figure 4) compare the result of powering an LTC1605 16-bit A/D converter using a bench supply with the result of powering the same converter with Figure 2's switching-regulator circuit. The residual error after taking the difference between the two corresponding differential and integral nonlinearity plots is within the test system's limit of error.

The results are impressive, but many underlying forces ultimately influence the final output noise. For example, theory



Noise, slew time, and efficiency are interrelated. Increasing the slew time decreases the noise with a 6% penalty in efficiency up to a point; increasing the slew time beyond 1.3 µsec reduces efficiency without further reducing noise.

FIGURE 5



The relationship between power-switch slew rate (Trace A) and output noise (Trace B) is clear. The highest slew rate (a) causes the most noise. Slower rates (b, c) decrease noise until you reach the slew rate that corresponds to the lowest noise performance (d).

LOW-NOISE SWITCHING REGULATORS

suggests that simply setting the transition rate to low values achieves low noise. Practically, such an approach is workable but wastes power during transitions, which lowers efficiency.

A compromise sets transition time at the fastest rate that also produces the desired noise performance. The LT1533's slew adjustments allow easy determination of this point.

The relationship between transition time and output noise for the low-noise switching-regulator circuit shows a greater than 5-to-1 noise reduction as switch transition time slows from 100 nsec (**Figure 5a**) to 1 μ sec (**Figure 5d**). In **Figure 5d**, the noise is lower than the photo displays because the probing-induced error that monitoring the switch causes corrupts the measurement.

Trade off slew rate for efficiency

You also need to consider the relationship among noise, slew time, and efficiency. Significant noise reduction coin-

cides with descending transition slow time until about 1.3 μsec (Figure 6); little additional noise benefit occurs beyond this point. A slow-time increase from 100 nsec to 1.3 μsec —the same region in which noise performance improves by a factor of five—results in a 6% loss in efficiency. Increasing the slow time beyond 1.3 μsec simply results in further efficiency losses without significant noise reduction, so operation in this region is undesirable.

In addition to choosing the slew rate, other factors help you achieve the lowest noise performance for your application. The filter capacitors you use should have low parasitic impedance. Sanyo OS-CON types are excellent in this regard and contribute to the performance levels that **Figure 2b** shows. Tantalum types are nearly as good. The input-supply bypass capacitor, which should reside directly at the transformer center tap, needs similarly good characteristics. Aluminum-electrolytic capacitors are unsuitable in low-noise circuits.

A PRACTICAL, LOW-NOISE MONOLITHIC REGULATOR

The low-noise, switching-regulator LT1533 IC includes feedback and error amplifiers, an oscillator, a comparator, output drivers, and a slew-control block. These functional blocks implement a fairly conventional push-pull architecture with a major exception. The push-pull approach continuously pulls current from the source and has good magnetics usage, meaning that power transfer is always occurring in the transformer, and the core stores no energy. The even and continuous current drain from the source eliminates

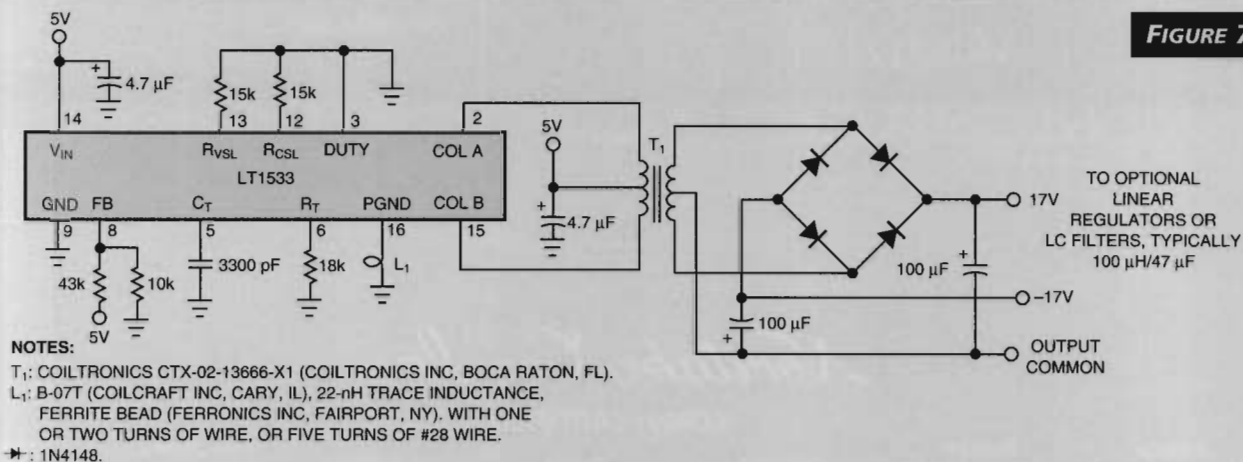
the fast, high-peak currents that flyback and other approaches require. This load is benign and does not corrupt the source.

The design's most significant aspect is the output stage. Each 1A output-power transistor operates within a broadband control loop. The IC senses the voltage across and current through each transistor, and the loop controls the slew rate of each parameter. External programming resistors independently set the voltage and current slew rates.

This patent-pending control tech-

nique of both the voltage and the current slew rates in the switches dramatically reduces high-frequency noise. This technique also controls noise in the other switching-regulator components—the catch diode and input and output capacitors.

The output-transistor switches also receive nonoverlapping drive, ensuring that they do not conduct simultaneously. Simultaneous conduction causes excessive and quickly rising currents, which degrade efficiency and generate noise.

**FIGURE 7**

Grounding the duty pin and biasing the FB pin puts the regulator into a 50%-duty-cycle mode. The circuit then produces a floating, unregulated output in proportion to T₁'s center-tap voltage.

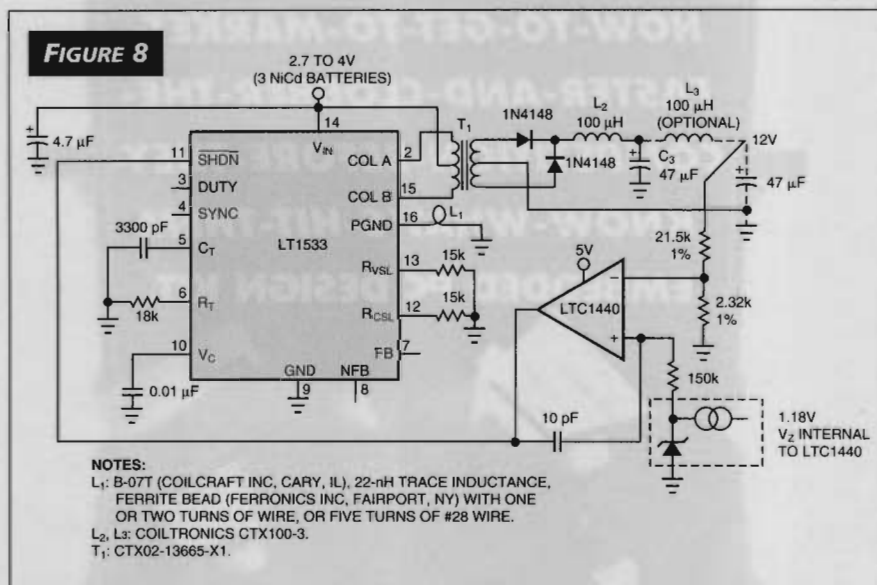
LOW-NOISE SWITCHING REGULATORS

Some circuits may benefit from a 330 Ω , 1000-pF damper network across the transformer secondary if the lowest noise is necessary. Excursions of 20 to 30 μ V can briefly appear during the switching interval when no energy is coming through the transformer. These events are so minuscule that they are barely measurable in the noise floor, but the damper eliminates them. Also, rigid adherence to low-noise measurement, layout, and breadboarding techniques are critical to low-noise performance. (An upcoming article details these techniques.)

Low-noise benefits

Based on Figure 2's basic circuit, you can design switching regulators with desirable characteristics, including low noise. These circuits include negative-output regulators, battery-powered regulators, floating-output regulators, low-quiescent-current regulators, high-voltage downconverters, and a 7500V isolated supply.

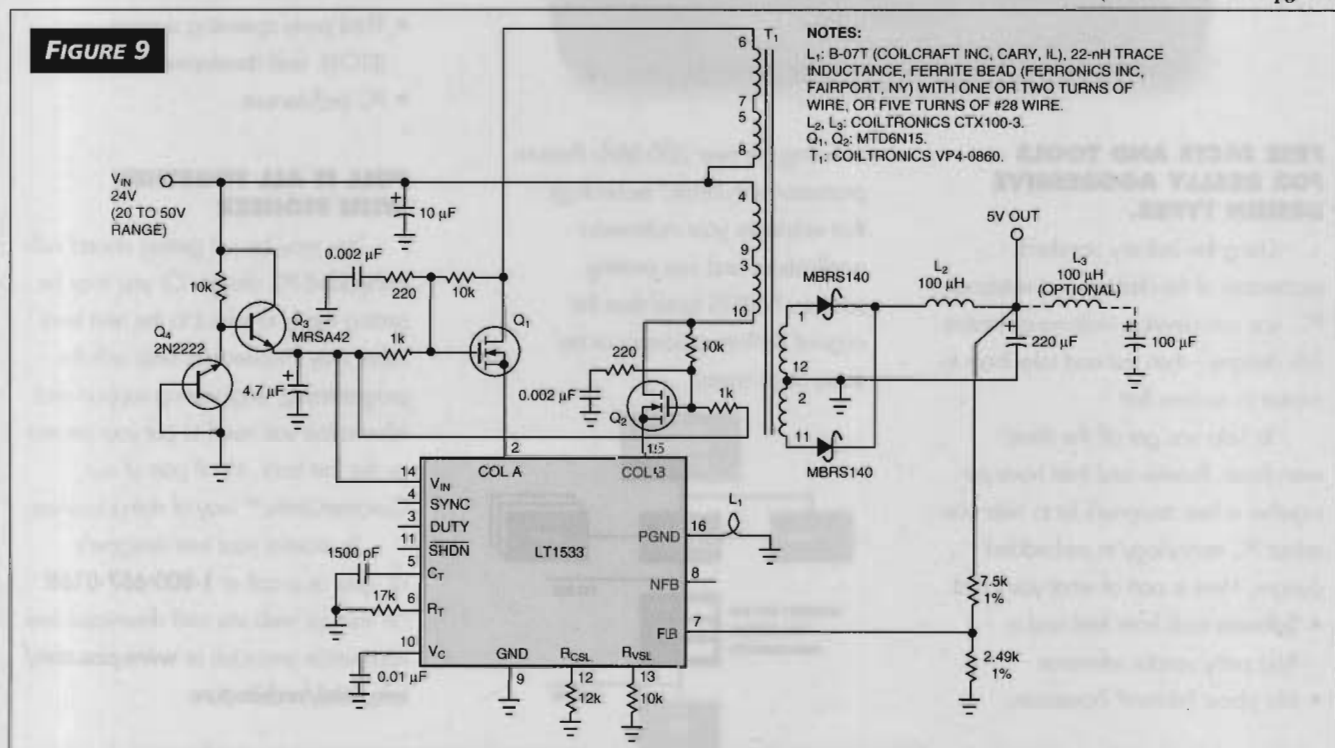
Transforming Figure 2a into a negative regulator is trivial because the LT1533 has a separate feedback input that directly accepts negative inputs. You simply feed back



A hysteretic burst-mode loop lowers quiescent current to 100 μ A and maintains output noise of 100 μ V.

the output to the negative feedback pin (NFB) instead of the FB pin. A slight change in the feedback scale factor—changing R_1 to 9.6 k Ω and R_2 to 2.4 k Ω —is necessary because of the higher effective reference voltage. You also

(text continues on pg 168)



A cascode stage comprising Q₁, Q₂, and related RC components can withstand 100V transformer swings from 20 to 50V inputs and permits the circuit to control a 5V, 2A output.

LOW-NOISE SWITCHING REGULATORS

need to reverse the polarity of the output capacitors.

Running Figure 2's 5-to-12V converter from three 2.7 to 4V NiCd batteries to produce a 5 or 9V output requires only changing R_1 and R_2 . For a 5V output, $R_1=15\text{ k}\Omega$ and $R_2=4.99\text{ k}\Omega$. For a 9V output with $100\text{ }\mu\text{V}$ of noise—the electronic equivalent of a 9V battery—you need only to change R_2 to $3.48\text{ k}\Omega$. All these changes result in the same low-noise performance as that in Figure 2.

Floating bipolar-output converter

Grounding the duty pin and biasing the FB input forces the IC into its 50%-duty-cycle mode. The circuit produces a full-wave-rectified output with respect to T_1 's secondary center tap, yielding bipolar outputs (Figure 7). Combining the forced 50% duty cycle with no feedback means that the outputs are unregulated and in proportion to T_1 's drive voltage. An output inductor is usually unnecessary. However, some inductance may be necessary at the highest output currents to limit inrush current; otherwise, the circuit may not start. For this circuit, you typically use optional linear regulators to provide regulation. With a linear regulator and output filter in use, noise is less than $100\text{ }\mu\text{V}$. Also, with linear postregulation, the 40-kHz fundamental components are undetectable. Removing the optional output filter allows linear-regulator contributed noise and switching spikes to rise, but noise is still less than $300\text{ }\mu\text{V}$ p-p.

Low-quiescent-current regulator

The LT1533 has a quiescent current of about 6 mA, and the circuit of Figure 2a takes approximately 10 mA. You can

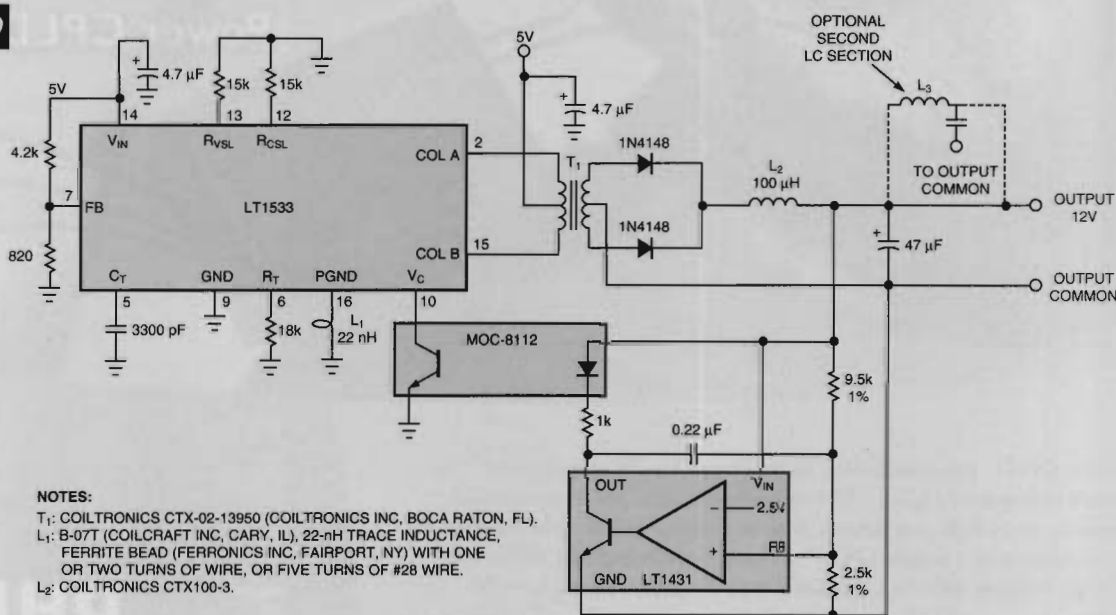
reduce the no-load quiescent current, which increases in proportion to the load, to $100\text{ }\mu\text{A}$ by running an on-off control loop around the device (Figure 8). The control loop replaces the normal error amplifier, achieving regulation by switching the IC in and out of shutdown in accordance with loop demands. A comparator, the LTC1440, compares a scaled version of the output with its internal reference and biases the regulator's shutdown pin. Using the phase shift, or time delay, of the output LC components provides loop hysteresis. In a normal continuously closed loop, you must minimize and compensate for this phase shift. In this case, the phase shift promotes the desired hysteretic control characteristic. Local ac-positive feedback at the comparator ensures clean transitions. The loop's on-off control characteristic causes low-frequency output noise that relates to the LC tank ring. No wideband components are observable, and the noise is still within $100\text{ }\mu\text{V}$.

Cascode design converts 24 to 5V

The LT1533's IC process limits collector breakdown to 30V. A complicating factor is that the transformer swings to twice the supply. Thus, 15V represents the maximum allowable input supply for Figure 2a's circuit. Many applications require higher voltage inputs, and you can use a cascoded output stage to achieve higher voltage capability. In a 24-to-5V converter (Figure 9), Q_1 and Q_2 , which sit between the IC and the transformer, constitute a cascoded high-voltage stage. These transistors provide voltage gain and isolate the IC from their large collector voltage swings.

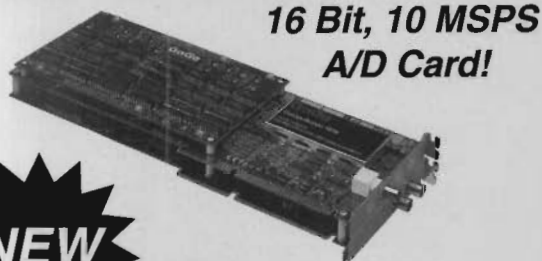
Normally, high-voltage cascodes simply provide voltage

FIGURE 10



Optoisolator feedback to the switching regulator's V_c pin closes the loop to produce a fully floating, regulated output with a 7500V peak-breakdown capability.

World's Fastest 16 Bit A/D Card



**16 Bit, 10 MSPS
A/D Card!**

NEW

CompuScope 1016

- ♦ 16 Bit Resolution
- ♦ Up to 10 MSPS Sampling
- ♦ 85 dB SFDR
- ♦ Up to 8 Meg Memory

GaGe

GAGE APPLIED SCIENCES INC.

1233 Shelburne Road, Suite 400, South Burlington, VT 05403

Tel: 800-567-4243 Fax: 800-780-8411

e-mail: prodinfo@gage-applied.com

web site: <http://www.gage-applied.com>

CALL 1-800-567-GAGE

Ask for extension 3403

CIRCLE NO. 12

From outside the U.S. contact Gage at 2000, 32nd Avenue Lachine, Montreal, QC, Canada H8T 3H7
Tel: (514) 633-7447 Fax: (514) 633-0770

High Frequency

SMD VCXO'S

ATM, SONET, SDH AND CLOCK RECOVERY



- STANDARD AND CUSTOM SPECIFICATIONS
- 155.52 MHz and 622.08 MHz VCXO's
- "J" LEAD CONFIGURATION OPTION
- COMPLIMENTARY OUTPUT OPTION
- ENABLE/DISABLE AVAILABLE
- 3.3 VOLTS AVAILABLE

RALTRON

2315 NW 107th Avenue

Miami, FL 33172 USA

Tel: 305-593-6033

Fax: 305-594-3973

E-mail: sales@raltron.com

Web Site: <http://www.raltron.com>



A WorldWide Manufacturer of:

- Microprocessor Crystals
- Clock Oscillators
- VCXO's, TCXO's, OCXO's
- Crystal Filters
- Ceramic Resonators
- Saw Devices
- VCO's

CIRCLE NO. 13

EDN

DESIGN FEATURE

LOW-NOISE SWITCHING REGULATORS

isolation. Cascoding the LT1533 presents special considerations because the circuit must accurately transmit, albeit at lower amplitude, the transformer's instantaneous voltage and current information to the IC. Otherwise, the regulator's slew-control loop does not function, dramatically increasing output noise. The ac-compensated resistor dividers that bias the base-drain junctions of Q_1 and Q_2 serve this purpose. RC gate-damper networks prevent transformer swings—which can couple into the IC via gate-channel capacitance—from corrupting the cascode's waveform transfer fidelity. The resultant cascode response is faithful in time and amplitude to the waveform swing at terminals 6 and 10 of the transformer, even with 100V swings. For output currents as high as 2A, noise is within a 400- μ V peak.

7500V isolated low-noise supply

Extremely high-voltage isolation is often necessary for circuitry that must withstand high common-mode-voltage effects. Adding an isolation stage permits a fully floating, regulated output with a peak breakdown capability of 7500V (Figure 10). This circuit's operation and characteristics are similar to those in Figure 2a but add the benefit of the isolated output. The LT1431 shunt regulator compares a portion of the output with its internal reference and drives the optoisolator with the error signals. The optoisolator's collector output biases the LT1533's V_C pin, closing a feedback loop to regulate circuit output. The 0.22- μ F capacitor stabilizes the loop.

EDN

Author's biography

Jim Williams, staff scientist at Linear Technology Corp (Milpitas, CA), specializes in analog-circuit and instrumentation design. He has served in similar capacities at National Semiconductor, Arthur D Little, and the Instrumentation Laboratory at the Massachusetts Institute of Technology (Cambridge, MA). A former student at Wayne State University (Detroit), Williams enjoys art, collecting antique scientific instruments, and restoring old Tektronix oscilloscopes.

VOTE

Please use the Information Retrieval Service card to rate this article (circle one):

High Interest
586

Medium Interest
587

Low Interest
588

www.ednmag.com

**Find the right processor,
at the right speed,
for the right price**

Do your own parametric search through EDN's
24th Annual Microprocessor Directory for
comprehensive details on over 700
microprocessors.